Motion Coordination and Programmable Teleoperation Between Two Industrial Robots

J.Y.S. Luh and Y.F. Zheng
Clemson University
Clemson, SC 29634

ABSTRACT

Tasks for two coordinated industrial robots always bring the robots in contact with a same object. The motion coordination among the robots and the object must be maintained all the time. To plan the coordinated tasks, only one robot's motion is planned according to the required motion of the object. The motion of the second robot is to follow the first one as specified by a set of holonomic equality constraints at every time instant. If any modification of the object's motion is needed in real-time, only the first robot's motion has to be modified accordingly in real-time. The modification for the second robot is done implicitly through the constraint conditions. Thus the operation is simplified.

If the object is physically removed, the second robot still continually follows the first one through the constraint conditions. If the first robot is maneuvered through either the teach pendant or the keyboard, the second one moves accordingly to form the teleoperation which is linked through the software programming. Obviously, the second robot needs not to duplicate the first robot's motion. The programming of the constraints specifies their relative motions.

1. INTRODUCTION

The motivation of using two coordinating robots to perform industrial tasks is to increase the overall productivity of the manufacturing process as compared to individual robot work without coordination capabilities. The use of the constraint conditions in the study of motion-coordination is introduced by Mason [1]. The constraint concept is extended and used in our earlier work [2,3] to plan coordinated motions of two robots in handling three different types of objects, two of them having their own degrees of freedom. In that study, the concept of holonomic constraints, which is applied to a system of rigid body dynamics by Wittenburg [4] and extended by us to robots with closed kinematic chain mechanisms [5], is adopted in the analysis. These constraints on the positions and orientations of the two robots must be satisfied at every time instant during the period of coordinated motion. To eliminate motion errors between them, one of them is assigned to carry the major part of the task. Its motion is planned accordingly. The motion of the second robot is to follow that of the first robot as specified by the relations of the joint velocities derived from the constraint conditions. Thus if any modification of the motion is needed in real-time, only the motion of the first robot is modified. The modification for the second robot is done implicitly through the constraint conditions. Specifically, when the joint displacements, velocities, accelerations of the first robot are known for the planned or modified motion, the corresponding variables for the second robot can be determined through the constrained relations.

Now, if the object is physically removed, the second robot still follows the first robot continually according as the specified equality constraints. In fact, the desired task determines the motion of the object and the motion of the first robot, which in turn specify the holonomic constraints between the robots. Once the constraints are programmed into the control computer to guide the motion of the second robot, this robot will follow the first one to satisfy the constraints even if the object is physically absent. Thus the second robot is maneuvered by the motion of the first robot through the control computer according to the programmed constraint conditions between them. If the object is ignored to begin with and the original holonomic equality constraints are replaced by a set of new constraint conditions that specifies the teleoperation relations between the two robots, then the realization of the programmable teleoperation is possible.

In the following, the coordination of two industrial robots handling an object is summarized and the experiments of the coordination are described. Their extension to the programmable teleoperation between the robots is then presented.

2. COORDINATION OF TWO INDUSTRIAL ROBOTS

Using Denavit-Hartenberg convention [6], each of the (n+1) links of a robot is assigned a coordinate system $(\underline{x}_i, \underline{y}_i, \underline{z}_i)$ for i=0,1,...,n, from the base link to the end-effector. The generalized coordinate, q_i, is the joint displacement of the link i either rotating about or sliding along z_{i-1} with reference to x_{i-1}. Also let $\underline{A}_{i-1}^{i}$ be the 4 by 4 homogeneous transformation matrix which transforms a vector with reference to coordinates $(\underline{x}_i, \underline{y}_i, \underline{z}_i)$ to the same vector with reference to coordinates $(\underline{x}_{i-1}, \underline{y}_{i-1}, \underline{z}_{i-1})$. Then

$$\underline{A}_0^n(\underline{q}) = \underline{A}_0^1(q_1)\underline{A}_1^2(q_2)\cdots\underline{A}_{n-1}^n(q_n) \qquad (1)$$

where $\underline{q}$ is an n-dimensional vector consisting of n joint displacements $q_1, q_2, \ldots, q_n$, can be represented by a coordinate frame

$$\underline{A}_0^n(\underline{q}) = \begin{bmatrix} \underline{n}(\underline{q}) & \underline{s}(\underline{q}) & \underline{a}(\underline{q}) & \underline{p}(\underline{q}) \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (2)$$

in which $\underline{n}(\underline{q}), \underline{s}(\underline{q}), \underline{a}(\underline{q})$ are unit vectors of coordinates, respectively, $\underline{x}_n$, $\underline{y}_n$ and $\underline{z}_n$ with reference to base coordinates; and $\underline{p}(\underline{q})$ is the position vector with reference to base coordinates, from its origin to the origin of $(\underline{x}_n, \underline{y}_n, \underline{z}_n)$. The orientation of the end-effector is specified by the upper-left 3x3 submatrix of $\underline{A}_0^n(\underline{q})$:

$$\mathbf{R}_e^n(\underline{q}) = [\underline{n}(\underline{q})\ \underline{s}(\underline{q})\ \underline{a}(\underline{q})] \tag{3}$$

which is also a rotation matrix. The Jacobian matrix $\mathbf{J}(\underline{q})=[\mathbf{J}_h^T(\underline{q}),\mathbf{J}_a^T(\underline{q})]^T$, where $(\ )^T$-transpose of $(\ )$, relates the linear and angular velocities of the end-effector with reference to base coordinators, $\underline{v}$ and $\underline{\omega}$ respectively, to $\dot{\underline{q}}$ according to

$$\mathbf{J}(\underline{q})\dot{\underline{q}} = \begin{bmatrix} \underline{v} \\ \underline{\omega} \end{bmatrix} \tag{4}$$

which leads to

$$\begin{cases} \mathbf{J}_h(\underline{q})\dot{\underline{q}} = \underline{v} \\ \mathbf{J}_a(\underline{q})\dot{\underline{q}} = \underline{\omega} \end{cases} \tag{5}$$

Three cases involving different types of objects are investigated in [2]. The results are summarized as follows:

Case 1. Two Robots Handling a Rigid-Body Object

Consider two robots each with n joints handling a rigid-body object, which is large and beyond the carrying capacity of one single robot. In order to move the object from one point to another, two robot end-effectors must grasp it at two specified points. It is assumed that the end-effectors furnish tight grips so that there are no relative motions among the end-effectors and the object.

For the purpose of convenience, one of the robots is named the leader and the other the follower.

Let $(\underline{x}_n^l,\underline{y}_n^l,\underline{z}_n^l)$ and $(\underline{x}_n^f,\underline{y}_n^f,\underline{z}_n^f)$ be the coordinato frames of end-effectors of, respectively, the leader. and the follower. Let $\underline{r}^l$ be the vector with reference to $(\underline{x}_n^l,\underline{y}_n^l,\underline{z}_n^l)$, from its origin to the origin of $(\underline{x}_n^f,\underline{y}_n^f,\underline{z}_n^f)$(Fig. 1). Then the holonomic constraints for the positions between the two robots are

$$\underline{p}(\underline{q}^l) + \mathbf{R}_e^n(\underline{q}^l)\underline{r}^l - \underline{p}(\underline{q}^f) = \underline{0} \tag{6}$$

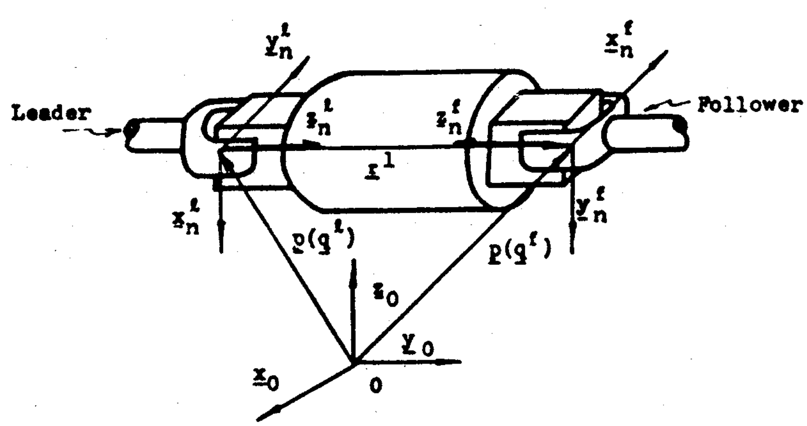

Figure 1. Two Robots Handling a Rigid-Body Object.

while the holonomic constraints for the orientations are

$$[\underline{n}(\underline{q}^f)\,\underline{s}(\underline{q}^f)\,\underline{a}(\underline{q}^f)]^T[\underline{n}(\underline{q}^l)\,\underline{s}(\underline{q}^l)\,\underline{a}(\underline{q}^l)] = \underline{U} \tag{7}$$

where $\underline{q}^l$ and $\underline{q}^f$ are, respectively, the n-dimensional vectors of joint displacements of the leader and the follower; and $\underline{U}$ is a 3 by 3 constant matrix and the values of its elements depend on the relative orientations between the two end-effectors. For the case of n=6, the constraint conditions relate the joint velocities of the follower to that of the leader as:

$$\dot{\underline{q}}^f = \underline{J}^{-1}(\underline{q}^f)\begin{bmatrix}\underline{J}_\lambda(\underline{q}^l) + \underline{L}^1(\underline{q}^l)\\ \underline{J}_a(\underline{q}^l)\end{bmatrix}\dot{\underline{q}}^l \tag{8}$$

where

$$\underline{J}^{-1}(\underline{q}^f) = \begin{bmatrix}\underline{J}_\lambda(\underline{q}^f)\\ \underline{J}_a(\underline{q}^f)\end{bmatrix}^{-1} \tag{9}$$

and

$$\underline{L}^1(\underline{q}^l) = \partial[\underline{R}_0^n(\underline{q}^l)\underline{r}^1]/\partial\underline{q}^l \tag{10}$$

Case 2. Two Robots Handling a Pair of Piers

Refer to Figure 2 and let O_1 be a point on the axis of plier's pivot between the two pieces. This axis is parallel to $\underline{y}_n^l$ and $\underline{y}_n^f$. Let $\underline{r}^2$ and $\underline{r}^3$ be, respectively, the vector with reference to $(\underline{x}_n^l,\underline{y}_n^l,\underline{z}_n^l)$ from its origin to O_1, and the vector with reference to $(\underline{x}_n^f,\underline{y}_n^f,\underline{z}_n^f)$ from its origin to O_1. Then, as indicated in Figure 2, the holonomic constraints for the position for this case are

$$\underline{p}(\underline{q}^l) + \underline{R}_0^n(\underline{q}^l)\underline{r}^2 - [\underline{p}(\underline{q}^f) + \underline{R}_0^n(\underline{q}^f)\underline{r}^3] = \underline{0} \tag{11}$$

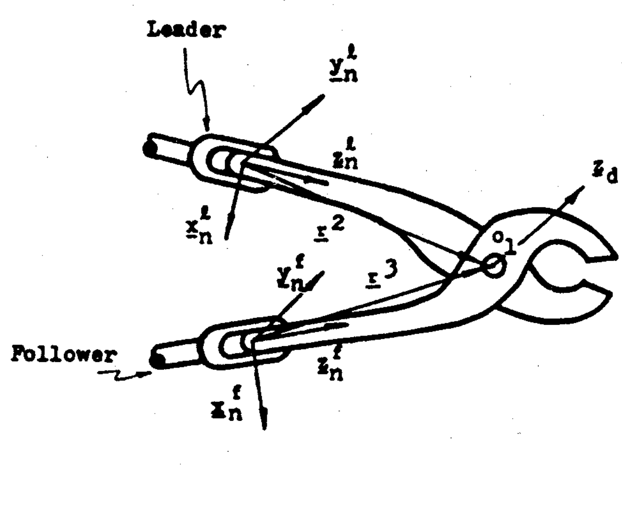

Figure 2. Two Robots Handling a Pair of Pliers.

The holonomic constraints for the orientation, however, reduce to

$$\begin{cases} \mathbf{n}^T(\mathbf{q}^f)\mathbf{a}(\mathbf{q}^\ell) = 0 \\ \mathbf{n}^T(\mathbf{q}^f)\mathbf{n}(\mathbf{q}^\ell) = 1 \end{cases} \tag{12}$$

since the normal vectors of the two end-effectors are always parallel to each other. For the particular geometry as shown in Fig. 2, an equation which relates the axis of the pivot, $\underline{z}_d$, to $(\mathbf{x}_a^\ell, \mathbf{y}_a^\ell, \mathbf{z}_a^\ell)$ can be written as

$$\mathbf{a}^T(\mathbf{q}^\ell)\mathbf{z}_d = 0 \tag{13}$$

This is also a constraint if one requires to hold the pliers without slippage. Let q_d be the angular displacement of the pivot joint of the object. The constraint conditions among the joint velocities of the two robots and the objects are, for the case of n=6,

$$\dot{\mathbf{q}}^f = \mathbf{J}_f^{-1}(\mathbf{q}^f)\{\mathbf{J}_\ell(\mathbf{q}^\ell)\dot{\mathbf{q}}^\ell - [0\ 0\ 0\ \dot{q}_d\mathbf{a}^T(\mathbf{q}^\ell)]^T\} \tag{14}$$

where

$$\mathbf{J}_\ell(\mathbf{q}^\ell) = \begin{bmatrix} \mathbf{J}_\lambda(\mathbf{q}^\ell) + \mathbf{L}^2(\mathbf{q}^\ell) \\ \mathbf{J}_a(\mathbf{q}^\ell) \end{bmatrix} \tag{15}$$

$$\mathbf{J}_f(\mathbf{q}^f) = \begin{bmatrix} \mathbf{J}_\lambda(\mathbf{q}^f) + \mathbf{L}^3(\mathbf{q}^f) \\ \mathbf{J}_a(\mathbf{q}^f) \end{bmatrix} \tag{16}$$

$$\mathbf{L}^2(\mathbf{q}^\ell) = \partial[\mathbf{R}_0^n(\mathbf{q}^\ell)\mathbf{r}^2]/\partial\mathbf{q}^\ell \tag{17}$$

and

$$\mathbf{L}^3(\mathbf{q}^f) = \partial[\mathbf{R}_0^n(\mathbf{q}^f)\mathbf{r}^3]/\partial\mathbf{q}^f \tag{18}$$

Thus, except at the singularity point of the follower, $\dot{\underline{q}}^f$ can be computed from (14) if $\dot{\underline{q}}^\ell$ and $\dot{q}_d$ are given.

If $\dot{q}_d$ is not specified, $\dot{\underline{q}}^f$ may have infinitely many solutions. However, the minimum norm solution which corresponds to the minimum energy solution [7] is:

$$\dot{\mathbf{q}}^f = \mathbf{J}^{f+}\mathbf{M}^2\mathbf{J}_\ell(\mathbf{q}^\ell)\dot{\mathbf{q}}^\ell \tag{19}$$

where

$$\underline{M}^2 = \left[\begin{array}{c|c} \mathbf{I} & \mathbf{0} \\ \hline & \mathbf{n}^T(\mathbf{q}^\ell) \\ \mathbf{0} & \mathbf{a}^T(\mathbf{q}^\ell) \end{array}\right] \tag{20}$$

and

$$\mathbf{J}^{e+} = [\mathbf{M}^2\mathbf{J}_l(\mathbf{q}^l)]^T\{\mathbf{M}^2\mathbf{J}_l(\mathbf{q}^l)[\mathbf{M}^2\mathbf{J}_l(\mathbf{q}^l)]^T\}^{-1} \tag{20a}$$

is the Moore-Penrose generalized inverse of $\{\mathbf{M}^2\mathbf{J}_l(\mathbf{q}^l)\}$[8]. Once the minimum norm solution of $\dot{\underline{q}}^f$ is determined, the expected resulting $\dot{q}_d$ can be obtained from (14) and (19) as

$$\dot{q}_d = [0\ \ 0\ \ 0\ \ \mathbf{a}^T(\mathbf{q}^f)]\,[\{\mathbf{I} - \mathbf{J}_l(\mathbf{q}^l)\mathbf{J}^{e+}\mathbf{M}^2\}\mathbf{J}_l(\mathbf{q}^f)\dot{\mathbf{q}}^f] \tag{21}$$

Case 3. Two Robots Handling an Object Having a Spherical Joint

Suppose that two robots handle an object consisting of two parts joined together by a spherical joint (Fig. 3). It is known that the spherical joint has three degrees of freedom. If the three degrees of freedom are specified by a velocity vector $\dot{\underline{q}}_d'$ of the spherical joint, then $\dot{\underline{q}}^f$ has the same form as (14) except that $\dot{q}_d\underline{s}^T(\underline{q}^l)$ is now replaced by $(\dot{\mathbf{q}}_d')^T\mathbf{R}_n^0(\mathbf{q}^f) = \{[\mathbf{n}(\mathbf{q}^f)\mathbf{s}(\mathbf{q}^f)\mathbf{a}(\mathbf{q}^f)]\dot{\mathbf{q}}_d'\}^T$. If, however, they are not specified, then there will be only three independent constraint equations associated with two coordinated robots [5]. As indicated in Figure 3, the coordinate and distance vectors are defined in a same manner as those in Case 2. When the holonomic constraints for the positions are imposed, the joint velocities of the two robots are related according to

$$\mathbf{J}^2\dot{\mathbf{q}}^l - \mathbf{J}^3\dot{\mathbf{q}}^f = \mathbf{0} \tag{22}$$

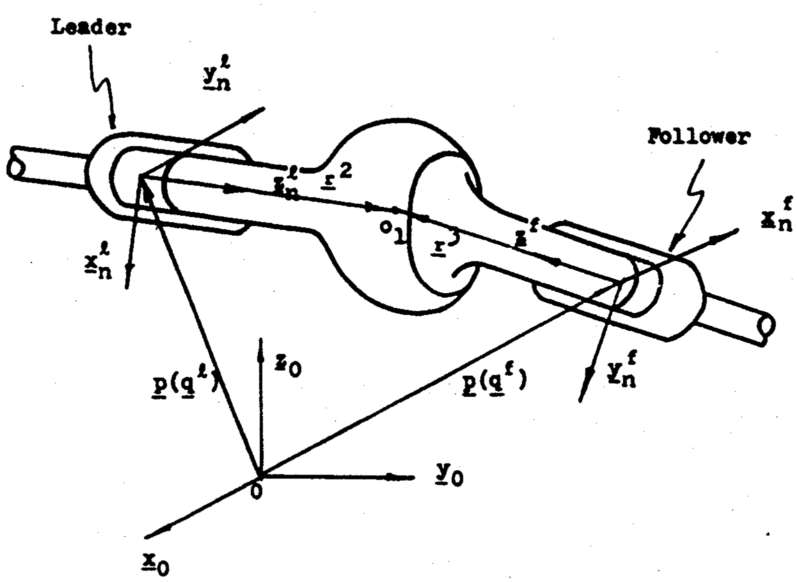

Figure 3. Two Robots Handling an Object Having a Spherical Joint.

where

$$\underline{J}^3 = [\underline{J}_\lambda(\underline{q}^f) + \underline{L}^3(\underline{q}^f)] \tag{23}$$

and

$$\underline{J}^2 = [\underline{J}_\lambda(\underline{q}^l) + \underline{L}^3(\underline{q}^l)] \tag{24}$$

The holonomic constraints for the orientation do not apply in this case. Thus, unless a three dimensional joint velocity of the object, which has three degrees of freedom in this case, is specified, equation (22) is the only constraint. Since $\underline{J}^3$ is a 3 by n $(n \neq 3)$ matrix, no unique solution for $\dot{\underline{q}}^f$ in terms of $\dot{\underline{q}}^l$ is possible. However, the minimum norm solution may be computed as

$$\dot{\underline{q}}^f = \underline{J}^+ \underline{J}^2 \dot{\underline{q}}^l \tag{25}$$

where

$$\underline{J}^+ = (\underline{J}^3)^T [\underline{J}^3 (\underline{J}^3)^T]^{-1} \tag{26}$$

is the Moore-Penrose generalized inverse of $\underline{J}^3$ [8]. Since $\underline{R}_o{}^n(\underline{q}^l)$ is an orthonormal matrix, then the expected resulting $\dot{\underline{q}}_d'$ corresponding to the minimum norm solution of $\dot{\underline{q}}^f$ may be obtained from (25) and the modified (14) as described above:

$$\dot{\underline{q}}_d' = [\underline{0}\ \underline{R}_n^0(\underline{q}^f)][\{\underline{L}_f(\underline{q}^f) - \underline{J}_f(\underline{q}^f)\underline{J}^+ \underline{J}^2\}\dot{\underline{q}}^l] \tag{27}$$

3. EXPERIMENTS OF MOTION COORDINATION OF TWO ROBOTS

Two experiments of coordinating two industrial robots corresponding to Cases 1 and 2 have been performed in the Robotics and Automation Laboratory of Clemson University. The first one involves handling a pail of water using two PUMA-560 industrial robots (Figure 4). Physically the two robots pick up the pail and change its orientation. Then they tilt the pail and pour the water into a bucket with a small opening. At the beginning, the two robots execute the point-wise coordination. Each robot's end-effector moves from its home location to the assigned handle of the pail. For this part of the coordinated-motion, the two coordinating local tasks are programmed through VAL-II language, and they reside in each of the two LSI-11 computers. The synchronization local task is programmed in the VAL-II command language and resides in DEC VAX-11/750 computer.

As soon as both end-effectors grasp the handles, the trajectory-wise coordination starts. The coordinating local task is programmed through C language, which resides in the VAX-11/750. The control flow goes through the following steps:

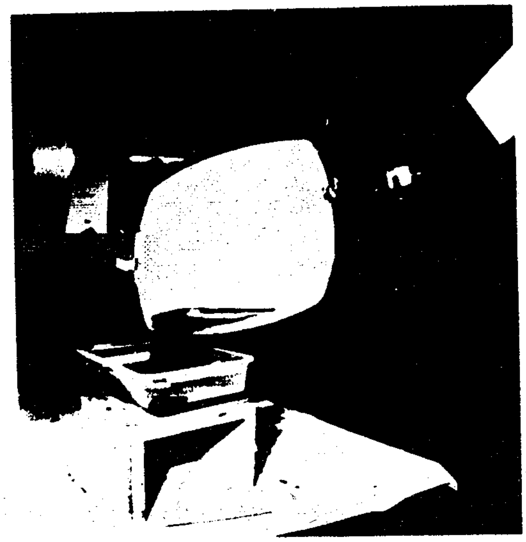

Figure 4. Handling a Rigid Object.

1. The Cartesian trajectory of the leader robot is programmed in the form of a string of set points in Cartesian coordinates according to the desired trajectory of the pail.
2. The Cartesian trajectory of the follower robot, in the form of a string of set points, is computed from the leader trajectory and the constrained equation, namely the coordination algorithm.
3. Let n=1.
4. Call Trajectory Planning process to convert the nth set point from the Cartesian coordinates to the joint coordinates for both leader and follower robots. In this step, the inverse kinematics of robot motion is involved.
5. Trajectory Planning process calls the Interprocessor Communication primitive to send the set points (in joint coordinates) to the Trajectory Execution processes.
6. Check if the last set point has been sent. If yes, stop; otherwise, let n=n+1 and go to step 4.

After the water is poured into the bucket and the pail is moved back to its original position, the point-wise coordination takes over again, and the two robots go back to their home positions.

The second experiment involves the two robots holding a pair of scissors and cutting a sheet of paper in the air (Fig. 5). The procedure is same as that of the first experiment except that the scissors have one degree of freedom of their own so that the constraint equation and hence the programming in C are more complicated. The detailed descriptions of the two experiments and the control computer structure are given in [9].

Other experiments of tightly fitted peg insertion, threading a nut onto a bolt, etc., are in progress. These experiments require force/torque compliances. A force/torque sensing wrist is mounted on the robot-follower which is force controlled. The robot-leader is then purely position controlled. As soon as the robots make an indirect contact physically, the force/torque feedback signals must be computed and processed through VAX 11/750. This additional burden of computation is significant which tends to decrease the band width and the sampling frequency. To speed up the computation, a floating point array accelerator is being mounted onto VAX 11/750. However, the experiments are still in progress.

Figure 5. Handling an Object with One Degree of Freedom. (A Pair of Scissors)

4. PROGRAMMABLE TELEOPERATION

In all the experiments described above, if the object(s) is(are) removed, the two robots will go through the same motion as if the object(s) were there. The motion of the leader is driven by the stored programming in VAX 11/750 while the follower is maneuvered through the programmed constraint conditions. If the leader is maneuvered through either the teach pendant or the keyboard, the follower's motion is still guided by the constraint conditions. In general, the constraint conditions may be written as

$$\underline{F}(\dot{\underline{q}}^{\ell}, \dot{\underline{q}}^{f}, \underline{\tau})=\underline{0} \tag{28}$$

where $\underline{\tau}$ is the force/torque signal measured by the sensing wrist.

It is seen that the processes of coordinated motion of two robots can be naturally extended to the teleoperation of the two robots provided the teleoperational tasks can be represented by equation (28) for every time instant and programmed in the control computer. In fact, the representation by equation (28) is not necessarily required so long as the tasks can be described sequentially and programmed accurately. Once the software programming is available in the control computer, the robot-follower may be teleoperated by the robot-leader whenever the latter is maneuvered through either the teach pendant or the keyboard.

5. SUMMARY

Coordinated motions of two industrial robots in handling an object, which may have its own degrees of freedom, can be achieved by employing the holonomic constraint conditions between the two robots at every time instant. The coordination is demonstrated with two PUMA-560 industrial robots controlled by a DEC VAX-11/750 computer. The motion coordination is then extended to the process of teleoperation between the two robots when the role of holonomic constraint conditions is replaced by the teleoperational tasks which are programmed in the control computer.

6. REFERENCES

1. M. T. Mason, "Compliance and Force Control for Computer Controlled Manipulators," IEEE Transactions on Systems, Man and Cybernetics, Col. 11, No. 6, June 1981, pp. 418-432.
2. Y. F. Zheng and J. Y. S. Luh, "The Control of Two Coordinated Robots," Proc. 24th IEEE Conference on Decision and Control, December 11-13, 1985, Fort Lauderdale, Florida, pp. 1761-1766.
3. J. Y. S. Luh and Y. F. Zheng, "Constrained Relations Between Two Coordinated Industrial Robots for Motion Control," International Journal of Robotics Research, MIT Press, Vol. 6, 1987.
4. J. Wittenburg, Dynamics of Systems of Rigid Bodies, Stuttgart: B. G. Teubner, 1977.
5. J. Y. S. Luh and Y. F. Zheng, "Computation of Input Generalized Forces for Robots with Closed Kinematic Chain Mechanisms," IEEE Journal of Robotics and Automation, Vol. 1, No. 2, June 1985, pp. 95-103.
6. J. Den avit and R. S. Hartenberg, "A Kinematic Notation for Lower Pair Mechanics Based on Matrices," ASME Transactions, Journal of Applied Mechanics, June 1955, pp. 215-221.
7. J. Y. S. Luh and Y. L. Gu, "Industrial Robots with Seven Joints," Proceedings of IEEE International Conference on Robotics and Automation, March 25-28, 1985, St. Louis, Missouri, pp. 1010-1015.
8. T. L. Boullion and P. L. Odell, Generalized Inverse Matrices, John Wiley and Sons, New York, 1971.
9. Y. F. Zheng, J. Y. S. Luh, and P. F. Jia, "A Real-Time Distributed Computer System for Coordinated-Motion Control of Two Industrial Robots," Proceedings of IEEE International Conference and Automation, March 31-April 3, 1987, Raleigh, North Carolina.